

PART III.

BLACK HOLES AND CENTRAL ACTIVITY

9. Black Holes in Galaxies

HST DETECTIONS OF MASSIVE BLACK HOLES IN THE CENTERS OF GALAXIES

H.C. FORD AND Z.I. TSVETANOV
The Johns Hopkins University
Homewood Campus, Baltimore, MD 21218

L. FERRARESE
The California Institute of Technology
Dept. of Astronomy, 105-24, Pasadena, CA 91125

AND

W. JAFFE
Leiden Observatory
Postbus 9513, 2300 RA Leiden, The Netherlands

Abstract.

After correcting spherical aberration in the Hubble Space Telescope in 1993, the central masses of galaxies can be measured with a resolution 5 to 10 times better than can be achieved at the best terrestrial sites. This improvement in resolution is decisive for detecting the gravitational signature of massive black holes in galaxy nuclei. The discovery of small ($r \sim 100 - 200$ pc) rotating gaseous and stellar disks in the centers of many early-type galaxies provides a new and efficient means for measuring the central potentials of galaxies. Concomitantly, VLBI observations of H₂O masers in the nuclei of NGC 4258 and NGC 1068 revealed exquisite Keplerian rotation curves around massive black holes at radii as small as 0.1 pc. Recent terrestrial *K*-band measurements of the proper motions of stars in the cluster at the center of the galaxy provide irrefutable evidence for a black hole with a mass of $2.7 \times 10^6 M_{\odot}$. At the time of this symposium, the presence of central massive black holes has been established in 12 galaxies. The evidence suggests that there are massive black holes in the centers of all AGNs and in most, if not all, nucleated galaxies. The present data show at best a weak correlation between black hole mass and bulge luminosity.

1. HST Resolution of a Black Hole's Sphere of Influence

HST has a stable, diffraction limited point spread function with a full width at half maximum of $0.048''$ at 486 nm. This resolution is 5 to 10 times better than the resolution achieved at the best terrestrial sites. To illustrate the importance of high spatial resolution, consider the line of sight velocity dispersion σ_{MBH} of stars near a massive black hole (MBH). This dispersion will be

$$\sigma_{\text{MBH}}^2 \sim GM_{\text{BH}}/R. \quad (1)$$

If the dispersion of stars in the bulge of the parent galaxy is σ_0 , the black hole's sphere of influence will be

$$R_{\text{BH}} \sim GM_{\text{BH}}/\sigma_0^2 = 43 M_8/(\sigma_{100})^2 \text{ pc} \quad (2)$$

where $\sigma_{100} = \sigma_0/100 \text{ km s}^{-1}$, and $M_8 = M_{\text{BH}}/10^8 M_{\odot}$.

A $10^8 M_{\odot}$ MBH in a galaxy like M31 with $\sigma_0 \sim 160 \text{ kms}^{-1}$ will have $R_{\text{BH}} \sim 5 \text{ pc}$. At the distance of the Virgo cluster, $R_{\text{BH}} \sim 0.2''$. Measuring the rise in the velocity dispersion toward the center is difficult but possible with HST, and presently impossible from the ground.

1.1. NUCLEAR DISKS

In addition to providing spatial resolution unobtainable from the ground, unexpected discoveries made with HST have revealed new ways to measure the gravitational potential in the centers of galaxies. HST observations of early-type galaxies have shown that small disks ($r \sim 100 - 200 \text{ pc}$) of gas or stars reside in the nuclei of many active galaxies (e.g., Jaffe et al. 1994 [J94], 1996). Because the disks are much larger than the parsec scale, hot, inner accretion disks, we refer to them as nuclear disks to avoid confusion.

Examples of the gaseous and stellar nuclear disks found in elliptical galaxies are shown in Figure 1. Table 1 summarizes our estimates of the disk masses derived from the $\text{H}\alpha$ luminosity and/or extinction maps and the assumption that the disks have the same dust-to-gas ratio as the galaxy.

The flattened, approximately circular nuclear disks are likely to be in near circular rotation in the central potential of the galaxy. The approximate alignment between the minor axes of the disk in NGC 4261 ($\Delta\theta = 17^\circ$) and NGC 6251 ($\Delta\theta = 25^\circ$) and the large scale radio axis suggest a causal connection between the angular momentum in the nuclear disk and angular momentum in the accretion disk. If the disk's circular motion persists inside of the black hole's sphere of influence, measuring the black hole's mass using emission lines in the disk will be much easier than using the

TABLE 1. Sizes and Estimated Masses of Gaseous Nuclear Disks

Galaxy	Distance (Mpc)	Radius (")	Radius (pc)	Inclination (Deg)	τ_V	$M_{\text{HI+HII}} (M_{\odot})$
NGC 4261	32	0.86	~ 130	64	~ 1	$\sim 5 \times 10^4$
NGC 6251	105	0.78	~ 400	76	~ 1.8	$\sim 3 \times 10^6$
M87	15	~ 1	~ 70	~ 40	—	$\sim 10^4$

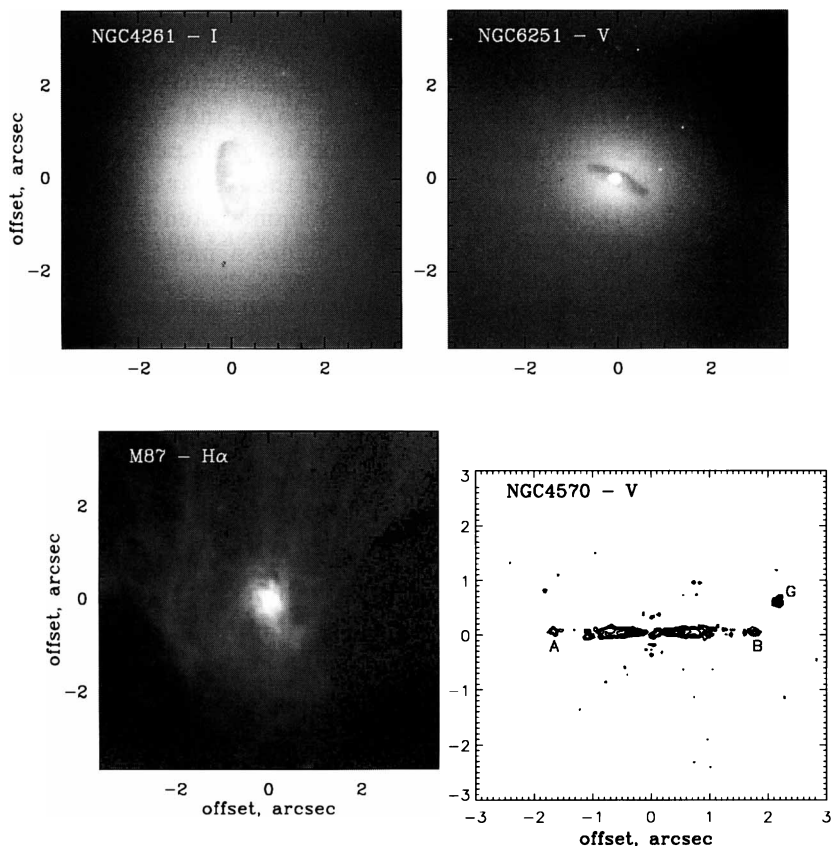


Figure 1. Examples of nuclear disks in early type galaxies. Two dusty nuclear disks are shown in the upper panels – NGC 4261 (*left*) and NGC 6251 (*right*). The two lower panels show the H α disk in M87 (*left*) and the stellar disk in NGC 4570 (*right*) after subtraction of the host galaxy.

stellar velocity dispersion. This was demonstrated by Ford et al. (1994) who used the newly installed WFPC2 to find a small ($r \sim 1''$; 70 pc at 15 Mpc) disk of ionized gas in the nucleus of M87, and Harms et al. (1994) used COSTAR with the Faint Object Spectrograph with a $0.26''$ aperture

to measure blue and redshifted rotational velocities of 500 km s^{-1} at radii $r = 18 \text{ pc}$ paired across the nucleus along the apparent major axis of the disk. These measurements yielded a central mass of $2.4 \pm 0.7 \times 10^9 M_{\odot}$ and a mass-to-light ratio $(M/L)_V \sim 500$. Subsequent measurements with the FOS $0.086''$ aperture (Ford et al. 1996) and the FOC (Macchetto et al. 1997) found Keplerian rotation around a $\sim 3 \times 10^9 M_{\odot}$. Likewise, FOS observations of the nuclear disk in NGC 4261 revealed a central mass of $4.9 \pm 1.0 \times 10^8 M_{\odot}$ and $(M/L)_V \sim 2100$ within the inner 14.5 pc (Ferrarese, Ford & Jaffe 1996).

Ford et al. (1997) reviewed gaseous nuclear disks in elliptical galaxies. They concluded that small, mostly dusty, nuclear disks and disk like structures are common in early type galaxies, with a frequency $\sim 30\%$.

J94 and van den Bosch et al. (1994) found small *stellar* nuclear disks in three Type II Virgo ESO (NGC 4342, NGC 4570, and NGC 4623). These disks have radii $r < 100 \text{ pc}$ and scale lengths $\leq 20 \text{ pc}$. The lower right panel in Figure 1 shows the isophotal map of the stellar disk in NGC 4570 after subtraction of the galaxy's bulge. As demonstrated by van den Bosch (1997), measuring these disks' rotation provides a means to measure the central mass.

2. Summary of HST Observations of Massive Black Holes

Table 2 summarizes HST estimates for dark masses in the centers of galaxies at the time of this writing. In addition to HST measurements, we have included the VLBA mass determinations because these observations have approximately 100 times higher angular resolution than achievable with HST. We also have included the mass determinations for the center of our Galaxy derived from ground-based infrared spectra and proper motions of the central star cluster (Eckhart & Genzel 1997; Ghez et al. 1998; Genzel 1998). These observations have 20 times higher spatial resolution than can be achieved with HST on M31 and M32.

The radial velocities of the masing disk in NGC 4258 show the unmistakable signature of Keplerian rotation around a mass of $3.6 \times 10^7 M_{\odot}$ interior to the inner edge of the disk at a radius of 0.13 pc (Miyoshi et al. 1995). The IR observations of the galactic center reported in these proceedings by Genzel and by Eckart & Genzel 1998, and Ghez et al. 1998, respectively find $2.7 \pm 0.2 \times 10^6 M_{\odot}$ and $2.6 \times 10^6 M_{\odot}$ inside 0.01 pc ! Maoz (1998) finds that the absolute maximum possible lifetimes of central dark clusters in the Milky Way and NGC 4258 are respectively $\sim 10^8$ and $\sim 2 \times 10^8$ years. Because this lifetime is much less than the ages of galaxies, a dark cluster is a highly improbable source for the mass. The galactic center and NGC

TABLE 2. High Spatial Resolution Observations of Massive Black Holes

Galaxy	Instrument	Resolution (mas)	References
NGC 6251	FOS	86	FFJ97
NGC 4486	FOS & FOC	260, 86, 63	H94; F96; M97
NGC 4261	FOS	86	FFJ96
NGC 4594	SIS & FOS	630(FWHM), 210	K96a
NGC 4374	STIS	200	B97
NGC 1068	VLBI	<0.5	GG97
NGC 224	FOS	260, 86	P98
NGC 3115	SIS & FOS	570(FWHM), 210	K96b
NGC 4258	VLBA	0.6 × 0.3	M95
Milky Way	NTT and Keck	130 – 150; 50	EG97, Gh98
NGC 4342	ISIS & FOS	1000(FWHM), 260	vdB97
NGC 221	FOS	210,86	vdM97

4258 are very strong cases that the central dark masses are massive black holes.

Table 3 summarizes the central masses, assumed to reside in massive black holes, derived from HST, VLBA, and IR observations. For each galaxy the table lists the total blue luminosity (BT_0), the ratio of the bulge/total luminosity, the bulge luminosity L_B , and the assumed distance. The last column is the reference for the mass determination method — GD = gaseous disk, SD = stellar dynamics.

The K -band luminosity of our Galaxy's bulge, $L_K = 1.2 \times 10^{10} L_\odot$ (Kent et al. 1991), was converted to a B -band luminosity by assuming that the galactic bulge has the same color as M31's bulge at 1 kpc, $(B - K)_0 = 4$ (Battener et al. 1986).

One outstanding question is whether or not there is a massive black hole in the center of every nucleated galaxy. Although the present census is too biased and incomplete to answer this question, the presence of MBHs in three local group galaxies make it clear that massive black holes are more likely to be the rule than the exception. A more restricted question is whether or not every active galaxy hosts a MBH. All eight of the AGNs in Table 3 have large central dark masses. As already noted, the active nuclei in NGC 4258 and the Milky Way are the two strongest cases for MBHs. These facts lend powerful support to the supposition that all AGNs are powered by accretion onto massive black holes. Ho (1997, 1998) finds that 40% to 50% of all nearby galaxies have active nuclei, suggesting that there is low to moderate levels of accretion onto a MBH in roughly half of all nearby galaxies. Taking into account the strong evolution of galaxy

TABLE 3. High Spatial Resolution Measurements of Black Hole Masses

Galaxy	Type RSA	Dist. Mpc	BT ₀ RC3	Bulge/ Total	M _{Bulge}	M _{BH} 10 ⁸ M _⊙	Method
NGC 6251	(E0)	98	13.22	1.0	-21.74	7.50	GD
NGC 4486	E0	16	9.49	1.0	-21.53	26.12	GD
NGC 4261	E3	32	11.36	1.0	-21.17	4.27	GD
NGC 4594	Sa+/Sb-	8.9	8.38	0.93	-21.13	9.67	SD
NGC 4374	E1	16	10.01	1.0	-21.01	3.00	GD
NGC 1068	Sb(rs)II	16.2	9.47	0.23	-19.98	0.16	H ₂ O Masers
NGC 224	SbI-II	0.72	3.28	0.24	-19.46	0.75	SD
NGC 3115	S01(7)	6.5	9.74	0.94	-19.26	14.07	SD
NGC 4258	Sb(s)II	6.4	8.53	0.23	-18.91	0.36	H ₂ O Masers
Milky Way	(Sc)	0.008	—	—	-17.79	0.027	SD
NGC 4342	E7	16	13.37	1.0	-17.65	3.20	SD
NGC 221	E2	0.72	8.72	1.0	-15.57	0.03	SD

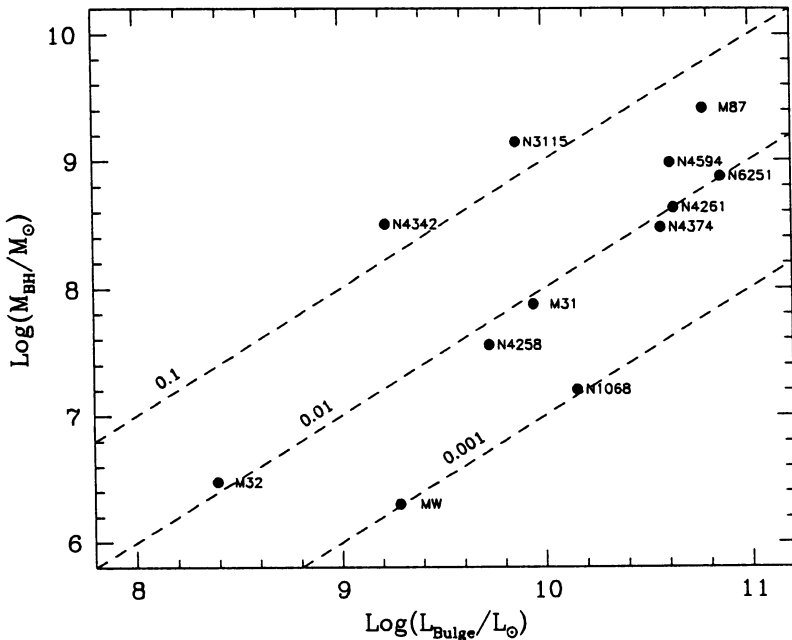


Figure 2. Black hole mass versus B-band bulge luminosity. The dashed lines are the locii of constant ratios of M_{BH}/L_{Bulge} .

activity with redshift, we are again led to the conclusion that most, if not all, galaxies host a MBH. Richstone (1998) comes to the same conclusion.

Using mostly ground-based data, Kormendy and Richstone (1995) made the interesting suggestion that there may be a strong relationship between

the mass of a galaxy's central black hole and the luminosity of the galaxy's bulge. If true, such a relationship would provide important clues as to how MBHs form and grow. To test their suggestion with more recent data, in Figure 2 we show $\log(M_{\text{BH}}/M_{\odot})$ versus $\log(L_{\text{Bulge}}/L_{\odot})$. The errors in the masses of the black holes are not yet well understood. In most cases we think the errors are likely larger than the formal errors given by the authors. However, the masses appear to be good to a factor of two or better. The luminosities of the bulges in NGC 4258 (Sb(s)II) and NGC 1068 (Sb(rs)II) are derived from Simien and de Vaucouleurs (1986) fraction of bulge light versus RC3 type, rather than from direct measurements. However, the bulge/total value of 0.23 is very consistent with Kent's (1987) value of 0.24 for M31 (SbI-II).

Figure 2 does not support the supposition that there is a strong relationship between black hole mass and bulge luminosity. The two galaxies with the best mass determinations, NGC 4258 and the galaxy, are separated by nearly a factor of 10 in this diagram. We further note that because it is difficult to measure the mass of a "small" black hole in a giant elliptical with low central surface brightness, the lower right hand corner of Figure 3 always will be difficult to populate.

In the next few years we can anticipate that the number of galaxies with HST measurements of central masses will increase by factors of several. This continuing census should provide definitive answers to questions about the frequency and ranges of black hole masses in galaxies.

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